Visuo-auditory sensory substitution for mobility assistance: testing TheVIBE

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Abstract. Although the principle of vision sensory substitution has been validated for over thirty years, its potential benefit for visually impaired people still remain largely untapped. The existing devices appears inefficient with respect to the actual problems impairing the daily life of visually impaired subjects. Recent advances in the comprehension of the signal processing in the visual system and about the visual process in itself offers new pathways for the improvement of these devices. However, a pre-requisite to any inquiries in this field is the establishment of new evaluation methods to assess the behavioral effect of these devices. Such methods should take into account the end user's need, should be carried in ecological environment, and should give results in a short time scale in order to be included in the conception loop of the device. In this study, we designed an experiment which match these criteria. We tested the effect of a recent visuo-auditory substitution system named TheVIBE on the mobility performance of twenty blindfolded subjects evolving in a maze on an indoor car park. Significant results were obtained with one hour of training only.

1 Introduction

Sensory substitution systems are devices that transmit the information usually coming from a particular modality, for instance visual information, via another modality, for instance the tactile or the auditory sense [1]. By substituting another sense to vision, vision sensory substitution devices offers a means to deal with blindness.

The principle of sensory substitution has been validated more than thirty years ago by Paul Bach-y-Rita [2]. In his experiment, he copied the image coming from a video camera onto a matrix of 20 by 20 vibrotactile pins embedded on the back of a dentist chair where the subject was sited. With such a device, blind subjects were able to recognize simple visual patterns.

Many technical developments were made since then. Portable tactile interfaces has been developed [3] [4] [5]. Moreover, the possibility to provide vision by means of the auditory system have been explored [6] [7] [8] [9]. In these latest devices, the information is transferred by means of simple headphones.

Many promising results have been obtained with sensory substitution systems. Capabilities of localization, character recognition, and objects discrimination were demonstrated on blind or blinfolded subjects in numerous studies ([2],

[8], [10], [11], [12], [13], [14]). The case of a blind subject working on a complex electronic assembly chain has been reported (Bach-y-Rita, 1995, cited in [11]). Finally, the cerebral plasticity induced by sensory substitution has been screened with PET [10], MEG [15] and fMRI [16].

Today, however, the potential benefit of sensory substitution for visually impaired people still remain largely untapped. Its use is restricted to a very limited population, and, to our knowledge, there is no available studies upon the practical use of vision substitution devices in blind peoples' everyday life. The existing devices appears inefficient with respect to the actual problems impairing the daily life of visually impaired subjects.

As they are a means to guide the designer toward the enhancement of its device, the methods used to evaluate the performances of visual sensory substitution systems should here be pointed at. The great majority of the behavioral evaluation tests are conducted on a one and only task: pattern (or character) recognition. To begin, this uncovered the large area of all the other capacities provided by vision (mobility, orientation, etc...) that can possibly impair visually challenged people to a greater extent [17]. Therefore, such methods are not likely to account for the overall performance of a device with respect to the VI users. Secondly, it should be noticed that pattern recognition is a task which much depends on the resolution of the device, and that the few hundred points available in current interfaces may not be appropriate to it. Finally, evaluation procedures are usually carried in carefully controlled laboratory environment, thus the results may not be generalized in daily living environments. To sum up, the actual evaluation methods may not be able to give a realistic insight into the practical interest of sensory substitution systems in VI users' every day life.

The development of new methods of evaluation is crucial for the development of visual prostheses from the designer's point of view. Recent advances in the comprehension of the signal processing in the visual system (see e.g. [18]) and about the visual process in itself (e.g. [19]) offers new pathways for the improvement of visual prostheses [20]. These considerations do not address the interfacing technology and thus can not be measured physically. The establishment of proper methods to study the behavioral effect of a device is thus a pre-requisite to any inquiries in this field. Such methods should provide realistic and quantitative information on the device's performance in usual tasks, particularly in those which most impair the VI users' every day life. Moreover, as they are bound to be included in the conception loop of the device, such methods should be able to give results in a short time scale, i.e. in minimalist conditions of learning.

In this paper, we present an experiment which match these criteria. The effect of a visuo-auditory substitution system was tested on the mobility performance of unsighted subjects evolving on a U-shaped maze in an indoor car park. Twenty blindfolded subjects took part on the experiment. The device significantly affected their mobility performances within one hour of training only.

2 Visual Impairment, Mobility and Visual Prosthesis

One of the highest impact of visual impairment in patients every day's life is undoubtedly the loss of independent mobility. According to a study established by the French Ministry of Health [17], 58% of the visually impaired subjects in physical condition to move declared having troubles with outdoor displacements, 29% declared not being able to move alone, and 15% can move alone only on particular itineraries. Total blindness and deep visual impairments also affect indoor mobility in 40% of the subjects.

Paradoxically enough, the use of the two most famous mobility assistive devices, the white cane and the guide dog, is not that common. In France, they have been adopted only by 2% in the overall VI population, with 26% in the blind population and 6% in the deeply visually impaired[17].

The limited use of guide dogs may be explained by their high cost : about $17000 for the overall cost and for a working period of 8 years [21]. On the other hand, the white cane is quite inexpensive (about 80$). It provides information about the user's immediate environment. With suitable learning, the white cane proved very useful for mobility [22]. Moreover, the cane identifies a blind traveler to other pedestrians or automobilists.

The main limitation of the white cane is its size, which limits the perimeter that can be scanned by the user. The long cane has a range of approximately two paces [23]. This does not give the user the opportunity to anticipate the path to follow [24] and thus limit walking speed (Hollins, 1989, cited in [25]). Moreover, the white cane does not prevent collision with upper body level obstacles (e.g. wall mounted public telephones...). Finally, even though the white cane may be used to find, verify, or discriminate landmarks, it is not likely to make the user retrieve his path if he lost it. Many electronic devices dedicated to mobility have been developed to overcome these limitations, but they do not reach a good market penetration (for a review, see e.g. [23]).

By giving access to a distant information, visual prosthesis are a potential candidate for mobility assistance. Two possible solutions can be considered : implants and sensory substitution systems.

A number of studies has been conducted in simulated implant vision conditions [26] [27] [28]. In those experiments, sighted subjects wore a head mounted display which screens a pixelized version of the incoming video camera image simulating the phosphenes vision that would be conferred by an implant. With such an equipment, subjects had to complete an indoor maze. Results suggested that a few number of stimulation points were likely to provide meaningful independent wayfinding abilities. However, no study is available on the mobility performance of actually implanted subjects.

For they are practical, removable, inexpensive and do not necessitate neither sophisticated material nor hazardous chirurgical operation, sensory substitution systems offers an interesting alternative to implants. To our knowledge, however, no study has been conducted on the interest of visual sensory substitution for mobility of VI people. The results obtained with simulation of implants are encouraging but the fact that they can be generalized to visual sensory substitution needed to be assessed.

3 The evaluation of mobility

Mobility is defined by Foulke as the ability to travel between locations gracefully, safely, comfortably and independently [29]. The most important aspects for walking were identified as : keeping balance, walking toward a goal, walking along a guideline, and walking along obstacle [30]. Many aspects should thus be taken into account for the evaluation of mobility.

A very interesting review on the means to evaluate Orientation & Mobility capacities particularly in the VI population can be found in [31]. One of the most common method to quantify O&M performance is to design a mobility course where the subject has to evolve. Typically, the time taken to complete the course and the number of mobility incidents are measured.

The weak point of such a method is that the course should be completed only once, otherwise the subject may learn it, and the effect induced by the device may not be disambiguated from the effect of memorizing the course [28]. Thus the subject cannot practice in the same course where he is tested.

One possible solution to cope with this problem is to design random courses so that the subject may be trained and tested in equivalent but not identical environment. An example may be found in Cha et al. [27] who used movable panel and piles to build courses. With this procedure the characteristics of the course such as its length, the number of obstacles, etc... were carefully controlled. However, such a procedure requires a relatively heavy installation. The other solution is to find similar courses in the whole environment (such as several corridors)[28] but the number of similar courses in a particular environment is usually restricted.

In VI peoples' every day life however, evolving on a completely new course is not usual. Most of the time, the user needs assistance to complete a well known course such as, for instance, the one between his home and his work place. In this study, we have thus decided to work on a one and only track.

This needed to be able to disambiguate the effect of learning the course from the effect induced by the device. To do so, the tests session was composed with two situation: one with the device working properly, and the other one with the device not working properly (the image was reversed with respect to the vertical axis). In both conditions, the effect induced by the memorization of the course was the same. The differences between these conditions thus reflected only the device's impact on the subject's mobility performances.

4 TheVIBE : a new visuo-auditory sensory substitution system

The device we used for the experiment converts the video stream from a video-camera into an auditory stream delivered to the user via headphones [9]. Such devices have already been developed [6] [7] [8]. They use an analogy between the visual space (top/bottom, left/right) and the auditory space (high tone/low tone, left panning/right panning). One of the major originality of TheVIBE with respect to the other devices is that the video-to-sound mapping is entirely configurable.

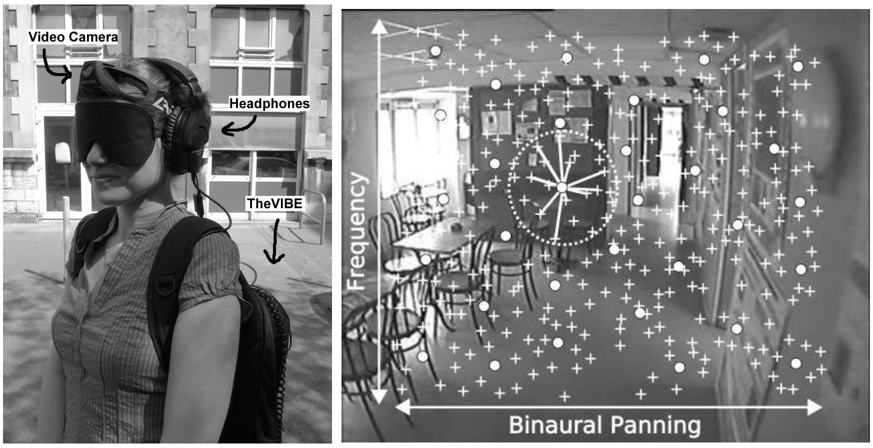

Fig. 1. TheVIBE device. TheVIBE is a software which converts the image coming from a video camera into sounds delivered to the user via headphones (left). The image-to-sound mapping in TheVIBE is entirely configurable. Sets of pixels (white crosses) grouped in receptive fields (circled part) are distributed uniformly on the video-camera picture (right). Each receptive field drives the loudness of a particular sound source, which frequency and binaural panning are determined respectively by the vertical and horizontal position of the receptive field's center (white squares).

TheVIBE is configured through a file, referred to as the device's "retina" This file contains the definition of the "receptive fields". A receptive field is a set of pixels usually covering a limited area in the image. A specific sound source is attributed to each receptive field. It is a sine waveform whose frequency, left/right amplitude panning and possibly interaural time difference are set in the "retina file". The state of the receptive field is defined as the mean value of gray levels in its area and drives the loudness of the corresponding sound source. The sound delivered to the user is the sum of the sounds produced by all the sources, thus giving instant access to the whole frame.

Following preliminary studies, the number of receptive fields in our study was set to 200. We first defined their center by distributing randomly 200 points on the image. We used then a Kohonen auto-organization technique [32] to control their density. For this study, the receptive fields' center were distributed uniformly.

Next, we distributed 10 sampled pixels randomly around each receptive field center following a Gaussian distribution. This defined the receptive fields. The standard deviation of the Gaussian was chose equal to 5 pixels. This ensured a sufficient overlap between the receptive fields to reduce aliasing [33].

The properties of the stereo sine waves attributed to each receptive field were calculated as follows. The horizontal position of the receptive field center (defined above) sets the inter-aural loudness difference of the sound source. This inter-aural difference ranges from -12 to +12 dB between the two ears, following a linear law (in dB) as reported by Blauert ([34], p 158).

The vertical position of the RF center sets the frequency of the sound source. In this study, we chose to use the Bark scale [35]. This scale is likely to minimize the masking effect between adjacent frequencies. The law to convert a usual frequency f (in Hz) into its corresponding bark value z is given in [36]:

$$z = \frac{26.81}{1 + 1960/f} - 0.53 \tag{1}$$

The frequencies are chosen so that the z value is proportional to the vertical position of the RF center. The min and max frequencies were respectively set to 300 and 3000 Hz.

Finally, since the sensitivity of the human auditory system to inter-aural time difference is quite variable in this frequency range [34], we have decided not to use this binaural cue.

5 Experimental procedure

The experiment took place in the laboratory's car park, which offers a suitable environment for a mobility test: large areas, simple geometry and controlled illumination. The track is composed by three segments forming a U-shape lighted by series of neon lights, and bordered by cars and piles (fig.2).

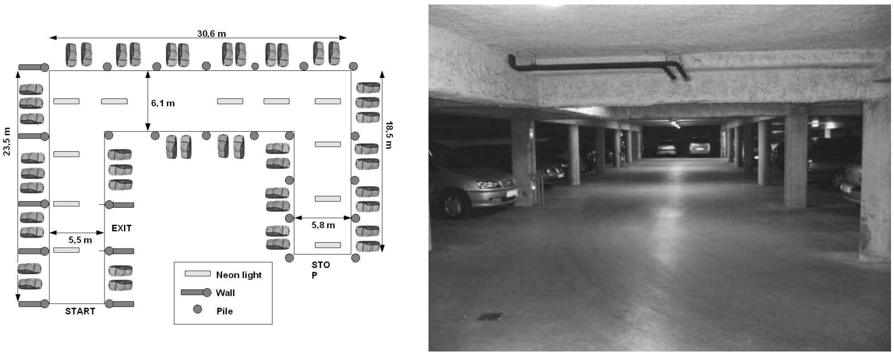

Fig. 2. The track in the car park was constituted by three segment in a U-shape (left). The track was lightened by neon lamps (right)

Subjects were blindfolded and equipped with The VIBE. They were solely told they would test a device which helps mobility for unsighted people by converting the image coming from the video-camera into sounds. No additional information was provided about the image-to-sound coding because it would not be likely to make sense for a blind user.

The experiment comprised four different sessions separated by at least 24 hours. The first three sessions were dedicated to learning, and the last one was the test session.

In the learning sessions, the subject had to complete the track three times. The first time, he is guided by the experimenter who held his arm. The two others, he has to complete it on his own, the experimenter giving only verbal cues when necessary. Left and right were the only available cues, and where given to orient the subject back on the track when he crossed its bound. The time to complete the track was measured (referred to as “Run Time”) as well as the number of time the subject crossed the bound of the track (referred to as “ Number of Contacts”).

For the subject, the last session was apparently completely similar to the previous one, except that he was told it was a test session. The first guided round was effectively carried in exactly the same conditions. However, in one of the two next non-guided rounds, the image coming from the camera was reversed with respect to the vertical axis. Under the hypothesis that the visual device does affect the mobility of the subject, this condition should induce a perturbation and differences should appear between the non-reversed (Normal) and the Reversed conditions. Normal and Reversed conditions order were counterbalanced between subjects. The experimenter was not aware of the actual order of the two conditions.

The reason why we did not compare performances with and without the device is because the two conditions are too different with respect to the user’s strategies. Indeed, without the device, the subject may concentrates on many cues, including sounds, temperature, breathe flow, etc..., while when using the device, he concentrates on the incoming sound. Moreover, without the device, the user is likely to walk as fast as possible while waiting for the experimenter’s verbal cues. To validate these considerations, an indicative measure of performance without the device was done after the experiment. Another possibility would have been to give the user a fake sound feedback, for instance coming from another subject’s session, but such a condition happens to be easily discernible and the subject would also have been likely to change its strategy.

Finally, such procedure is likely to maximize the observed effect: the more the device is used in the regular condition, the more it perturbed the subject in the reverse condition. This maximization is of particular interest here since the short learning time is likely to imply a short effect.

6 Subjects and Apparatus

Twenty normally sighted and hearing subjects took part in the experiment. Their ages range from 22 to 38 with mean value 26 and standard deviation 4.5. Three of them were not completely naive about the device : they had completed an experiment on localization with a previous version of the device one year ago [20]. Their results were not significantly different from the rest of the group.

Subjects were blindfolded and equipped with a BlackEye2 frontal video camera covering a 92 degrees field of view. Geometrical deformation induced by the wide-angle lens was corrected using the Camera Calibration Toolbox for Matlab [37]. The camera was connected to a Dell Latitude D620 laptop computer with a 2 Ghz INTEL Centrino Duo processor via a Pinnacle USB PCTV tuner. The 320x240 video stream was converted into a sound stream by TheVIBE. The auditory stimulation was conveyed thanks to a pair of Sennheiser HD 280 Pro headphones.

7 Results

Statistical analysis on the results were carried with R [38]. Learning sessions and Test session were analyzed separately.

7.1 Learning

The time subjects took to complete each non-guided trial as well as the number of contacts were recorded in each learning session. Mean run time and number of contacts were computed and compared (fig. 3).

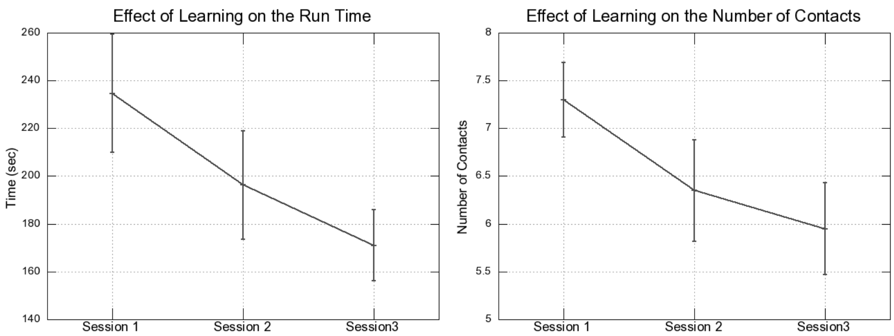

Fig. 3. Effect of learning on the subject performances

Effect of learning was assessed using a Friedman non-parametric test of variance for paired groups on the three learning sessions for Run Time (RT) and

Number of Contacts (NC). Learning had a significant effect on both of them ($p < 0.01$ for both).

An analysis of contrasts gives a further insight into this question. Performance in both RT and NC improved between the first session and the last two sessions (Student t-test, $p < 0.05$ for both). No significant difference was found between the last two sessions (p = 0.09 for RT and p = 0.53 for NC). This suggests that the number of learning sessions was appropriate.

7.2 Test

Data Processing In the Test session, RT and NC were measured in each of the two conditions (Normal and Reversed). However, we divided each of them by their mean value in both conditions, giving thus Relative Run Time values (RRT) and Relative Number of Contacts values (RNC).

$$RRT = \frac{2RT}{RT(Normal) + RT(Reversed)} \tag{2}$$

$$RNC = \frac{2NC}{NC(Normal) + NC(Reversed)} \tag{3}$$

Such a processing is likely to eliminate the variance due to interindividual differences, and thus enhance the sensitivity of our measures.

Results are shown in fig.4

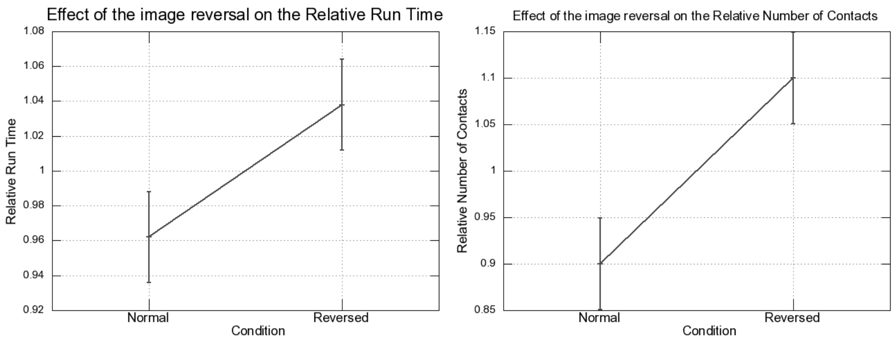

Fig. 4. Effect of the image reversal on the subjects performance

Data Analysis In both Normal and Reversed conditions, the RRT and RNC distribution can be considered as being Gaussian (Shapiro test for Gaussianity, $p > 0.05$), thus we performed a unilateral Student t-test for paired groups to assess the significance of the observed differences. The hypothesis was that indicators in the Normal condition were lower than in the Reversed condition.

The values obtained for the Relative Number of Contact in the Normal condition were significantly lower than in the Reversed condition (Student t-test, t(19)=2.02, $p < 0.05$). Mean values were respectively 0.9 ± 0.05 in the normal condition, versus 1.1 ± 0.05 in the reversed condition giving a relative difference of performance of 20 ± 10 %.

Significance threshold was not reached for the Relative Run Time, but this indicator showed a strong tendency toward our hypothesis (Student t-test, t(19)=1.43, $p < 0.01$). Mean values were respectively 0.962 ± 0.026 in the normal condition, versus 1.038 ± 0.026 in the reversed condition giving a relative difference of performance of 7.5 ± 5.3 %

7.3 Discussion

Our results demonstrates that theVIBE device has a positive effect on the mobility performance of blindfolded subjects. Indeed, the Relative Number of Contacts is significantly lower in the Normal condition than in the Reversed condition.

Results obtained on the Relative Run Time however do not reach significance. This suggests that the RRT indicator is less sensitive than RNC. A mean to increase the effect of the device on the Run Time would be to set a longer track. Indeed, if L is the length of the track, V_1 and V_{-1} the preferred walking speed of the subjects respectively in the Normal condition and in the Reversed condition, we obtain the following difference on Run Time:

$$\varDelta RT = (V_1 - V_{-1})L \tag{4}$$

The effect of the walking speed on the Run Time is proportional to the track's length. However, the indicator we used in this experiment, the Relative Run Time, is not dependent on the track length. Indeed:

$$\varDelta RRT = 2\frac{(V_1 - V_{-1})L}{(V_1 + V_{-1})L} = 2\frac{(V_1 - V_{-1})}{(V_1 + V_{-1})} \tag{5}$$

Thus, increasing the sensitivity of the time indicator by increasing the track length would imply not to use the Relative Run Time but merely the Run Time as indicator. This would be likely to increase the noise due to interindividual differences. There is no evidence as to which solution would be best.

Finally, we have not compared, in this study, a situation were the subject uses the device to a subject were he does not because we considered that the subject was likely to use different strategies. To verify these aspects, we made a post-experiment measure of the subjects performance without the device (although blindfolded). Results indicate that subjects are faster without the device (148 ± 12 sec against 170 ± 18 sec while using the device), but make more contacts (7.8 ± 2 contacts against 5.4 ± 2 with the device). Interpretation of these results would be difficult if not considering different strategies.

8 Conclusion

In this study, we showed the effect of a new visuo-auditory substitution system on the mobility of blindfolded subjects following a track in an ecological environment. The device affected the trajectory of subjects, measured as the number of times a subject crossed the bounds of the track. The few number of stimulation points employed (200) confirms previous experiments in simulated visual prosthesis conditions [28].

The experimental procedure we have developed presents two main advantages with respect to the other procedures. Firstly, it properly disambiguates the effect of learning the track from the effect induced by the device without using several different tracks: the whole experiment can be conducted on a one and only track. Secondly, the experimental procedure makes it possible to get rid of the inter-individual variability between subjects with respect to their overall performances, thus enhancing the sensitivity of our variables. The fact that we obtained significant results after such a short learning time (three sessions of twenty minutes each) and in such noisy ecological conditions (the car park was not supervised during the experiment) is likely to be explained for a great part by this latest aspect.

These results however are more interesting from the designer's point of view than from the end user's one. Indeed, in this study, we did not compare a situation were the subject use the device to a situation were he does not, mainly because the strategies employed by the subject were different. Thus, assessment of the practical interest of the device for mobility of VI's subjects would require further investigations. Nevertheless, the more the device as an impact on the mobility of the subject in our experiment, the more it is likely to be practically efficient. Thus, our experiment is suitable for the optimization of a visual prosthesis with respect to the end user's need, a necessary step toward the conception of useful assistive devices for the visually impaired.

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